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FOR

ENVIRONMENTAL QUALITY

EXPOSURE OF THE HAND TO VIBRATION IN INDUSTRY

by

A.J. Brammer

Prepared for the Subcommittee on Physical Energy Phenomena

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α "Vibration Effects on the Hand and Arm in Industry", published by John Wiley & Sons, New York (1982):

Introduction: p 1, lines 4-25, 40-43; and p 2, lines 10-45.

Section I: p 2, lines 61-99, 105-121, 127-132; p 3, lines 1-25, 32-68, 76-89, 115-133; p 4, lines 1-19, 23-46; p 5, lines 7-92; p 6, lines 104 - p 7, line 33; p 9, lines 77-87, 101-113, 120-125; and p 10, lines 1-34.

Section III: p 291, lines 40-45; p 292, lines 1-13, 66-78; p 293, lines 6-36; p 294, lines 20-33, 41-48, 59-76; p 295, lines 1-13, 31-34; p 296, lines 1-15, 27-38; p 297, lines 1-63, 69-89, 93-108; and p 298, line 1 - p 299, line 11.

Journal of Low Frequency Noise and Vibration, Special Volume #1 (1983), published by Multi-Science Publishing Co. Ltd.

Section II: p 151, lines 3-15; p 152, lines 21-25, 29-55; p 153, lines 1-14, 27-33, 38-56; p 154, lines 1-8, 26-49; p 155, lines 1-2, 11-39.

EXPOSURE OF THE HAND TO VIBRATION IN INDUSTRY

BY

A.J. BRAMMER

NRCC No. 22844

PREFACE

The constant emphasis on increased production and efficiency in industry has meant that hand-held power tools and other machines and industrial processes involving hand-arm vibration are being used more and more. In Canada alone, it is estimated that over 200 000 workers in the mining, forestry, metal-working, automotive, construction and other industries are exposed to vibration and so potentially run the risk of injury and illness from that source. The extent of the problem is extremely difficult to ascertain from medical records for, in the past, the complex of symptoms were often not recognized by doctors nor diagnosed as being related to vibration. The subject has suffered significantly because of this.

This study is aimed at determining the consequences of repeated exposure of the hand to vibration in industry. It was prepared by Dr. A.J. Brammer of the Division of Physics, National Research Council of Canada, at the request of the Physical Energy Phenomena Subcommittee of the National Research Council's Associate Committee on Scientific Criteria for Environmental Quality.

Three papers by the author served as the basis for this document:

1) Vibration effects on the hand and arm in industry: An introduction and review (co-authored with Dr. W. Taylor);

2) Threshold limit for hand-arm vibration exposure throughout the workday; and

3) Dose-response relationships for the hand-arm vibration syndrome with reference to neuro-vegetative effects.

The first two papers have been published in: "Vibration Effects on the Hand and Arm in Industry" (Brammer and Taylor 1982) and the third appeared recently in the Journal of Low Frequency Noise and Vibration (Brammer 1983a).

INTRODUCTION

Operators of chain saws, rock drills, chipping hammers, pedestal grinders and many other power tools and machines, and those involved in industrial processes have long been aware of tingling, numbness and blanching of their fingers. Episodes of "white fingers", "waxy fingers", "dead fingers" or "dead hand" were first reported in the literature between 1911 and 1920, in studies by Loriga (1911), Hamilton (1918) and Rothstein (1918). The spasm of the arteries in the fingers was correctly attributed to vibration of the rotary-percussive air-driven drills commonly used by stonecutters and rock miners at that time. It was also recognized that the vascular signs and symptoms resembled the spontaneous vasoconstrictive phenomena induced by exposure to cold, first described by Raynaud in 1862, "where persons who are ordinarily females see under the least stimulus one or more fingers becoming white and cold all at once, the determining cause being the impression of cold" (Raynaud 1888). This clinical entity, found in from 5 to 10% of the female population and occasionally in males (otherwise normal, healthy persons) is known to this day as Primary Raynaud's Disease (or constitutional white finger). Its underlying pathophysiology has not yet been established, but there are strong hereditary and psychosomatic components. Similar signs and symptoms are now known to result also from injury to the hands and certain diseases, and these are referred to as Secondary Raynaud's Phenomenon.

The close association between white finger attacks and vibration entering the hands was responsible for the introduction of the descriptive term "vibration-induced white finger" (VWF), though the condition is still known as "traumatic vasospastic disease" in parts of Europe. However, tingling, numbness and prickling of the fingers are commonly experienced, with loss of fine touch, pain and temperature sensation between vasospasms in advanced cases. There is also some evidence of reduced grip strength, of bone cysts in the fingers and wrists, of joint degeneration in the wrist and elbow, and of vegetative responses implying the involvement of the central nervous system. With increasing appreciation of the effects of vibration on the hand and arm (Teleky 1938; Klimkovã-Deutschovã 1966; Hasan 1970; Kumlin et al. 1973; Pyykkö 1976; Färkkilä et al. 1982), the nomenclature for this clinical entity clearly required expansion. The complex of VWF and the associated pathology occurring in other systems, in addition to the arterial system, are now termed the Vibration Syndrome or, more precisely, the Hand-Arm Vibration Syndrome (HAV Syndrome), to distinguish them from disorders caused by whole-body vibration.

Acceptance of the HAV Syndrome as an industrial disease has been hampered by several factors:

1) the lack of recognition of the HAV Syndrome by physicians;

2) the difficulty of distinguishing between the HAV Syndrome and other causes of similar signs and symptoms;

3) the apparent trivial nature of the impairment in cases where there is no evidence of reduced work performance or of any time lost, on or off the job;

4) the lack of an objective or psychophysical measure of the severity of the condition (cf. the determination of hearing thresholds by audiometric methods to establish the extent of noise-induced hearing loss), much reliance for diagnosis resting on the person's own subjective history of the frequency and extent of attacks, and interference with activities; and

5) the lack of an accepted measure of and tolerable limit for vibration exposure.

In this monograph, the consequences of repeated exposure of the hand to vibration in industry are explored. Occasional use of hand-held power tools in industry and casual use of consumer products are thus not considered, nor is exposure of the whole body to vibration. The signs and symptoms commonly associated with the HAV Syndrome are introduced in Section 1, together with their underlying pathophysiology and their classification by severity. The factors influencing the severity of vibration exposure are next discussed, as well as possible procedures for restricting the adverse health effects associated with habitual exposure. The few dose-response relationships constructed for components of the HAV Syndrome are then reviewed in Section 2, followed by a discussion in Section 3 of methods for defining a vibration level that can be tolerated throughout the workday.

1.0 EFFECTS OF VIBRATION ON THE HAND AND ARM

1.1 SIGNS, SYMPTOMS AND PATHOPHYSIOLOGY OF COMMON DISORDERS

The first symptoms experienced after commencing an occupation in which vibration is transmitted to the hands consist of tingling and numbness. The fingers may also become swollen and inflexible, though these symptoms frequently subside during the weekend break from work. With further exposure to vibration, commonly measured in years, a white fingertip appears. This episodic blanching of fingertips is generally precipitated by cold, but the link between this sign and vibration is often not evident to those affected. The time interval between the commencement of exposure and the appearance of the first white fingertip is known as the latent interval for finger blanching, and is related to the rate at which vibration enters the hand: the shorter the latent interval, the more rapid the progression of disorders. With continuing exposure, the area blanching during an attack extends from the tip to the base of the finger. By this time several fingers may be involved, principally those in contact with the most intense vibration (Färkkilä et al. 1978), so that the affected areas are often asymmetrically distributed on the hands, as can be seen from Figure 1-1 (Rothstein 1918). Ultimately, three or four fingers on each hand are subject to vasospasms, the thumb usually being the last to succumb.

The symptoms produced by arterial ischemia, namely blanching, venostasis and reactive hyperemia (all usually provoked by a cold stimulus) are the main phenomena of the HAV Syndrome. Of equal concern as the vasospasms, however, is the involvement of the peripheral nerves, as evidenced by the numbness and paresthesia, which frequently affect larger areas (see Figure 1-1). These symptoms can cause disturbance of sleep by awakening the worker, and are probably associated with degenerative changes in the mechanoreceptors (Walton 1974). In addition, there are measurable reductions in tactile sensitivity (Pelmear 1973), grip strength (Färkkilä et al. 1982), and manual dexterity (Banister and Smith 1972). The neurological and muscular changes develop concurrently with the vasoconstrictive process, but recent evidence suggests that they may occur independently (Pyykkö et al. 1982).

In advanced cases the episodes of blanching are replaced by a persistent cyanotic appearance of the fingers; the ability of the blood vessels to constrict and dilate is lost, and the blood flow is impeded. This may lead to malnutrition and atrophy of the skin at the fingertips, resulting in tissue necrosis and gangrene in a small number of cases. Fortunately, these late manifestations of VWF are rare, since severe cases usually withdraw from work that involves vibration exposure. Regrettably, it is the worker who, unwilling to transfer to other employment and so lose his acquired skills, is most at risk.

The vascular tree within the fingers appears to be the main target. Blood flow is reduced with occlusion of the digital artery,

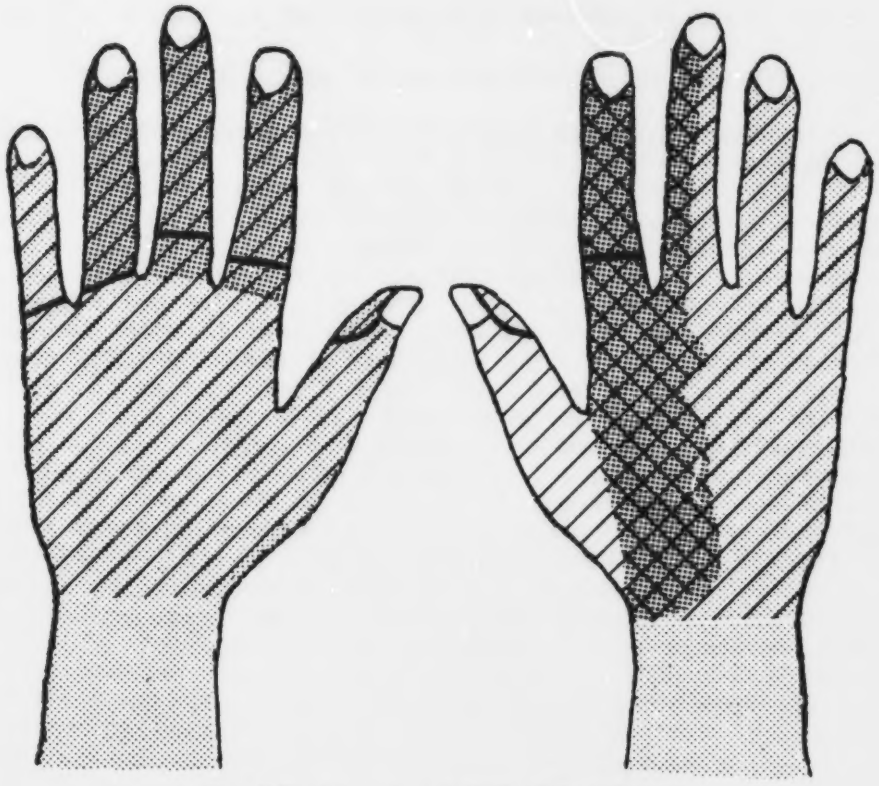

Figure 1-1. Hands of a 28-year-old stonecutter showing the signs and symptoms after seven years of operating an air hammer (the most recent five involved year-round exposure to vibration). The decreases in the sense of touch and pain were determined by traditional neurological tests, and the margin of the areas blanching, indicated by the broad black line, was found by immersing the hands in cold water (adapted from Rothstein 1918).

both during a VWF attack and in the basal resting state, and especially under conditions produced during "cold" provocation. Raynaud assumed that the vasoconstriction was due to overactive sympathetic nerve control of the digital arteries and that the excess activity following a cold stimulus was the basis for the episodic attacks. Despite the attraction of this theory (and following 120 years of further speculation), it has never been substantiated. Also, the many treatments directed towards minimizing sympathetic control of the vasomotor tone, including cervical sympathectomy, have been unsuccessful. When sympathetic nerve activity is severed surgically, immediate dilation of the peripheral vessels is observed; but in a matter of six to eight months, episodic attacks are again in evidence. The adrenergic sympathetic fibres constrict the digital arteries but the latter have no vasodilatory fibres supplying them. Reflex dilation occurs only when the sympathetic influence is removed.

Thus, the vasomotor tone must be influenced directly by "local" factors, including chemical mediators such as serotonin and prostaglandins and in particular by thromboxane A2 (a potent vasodilator). The interaction of these compounds is believed to control the laying down (and clearance) of platelet thrombi within the vasculature (Moncada et al. 1977). Advanced cases of Primary Raynaud's Disease and Secondary Raynaud's Phenomenon with tissue necrosis and ulceration are found to have thrombi in the small digital vessels (Lewis and Pickering 1934; Lewis 1938; Pickering 1951). They are also seen in advanced VWF cases (James and Galloway 1975). In all of these, raised blood viscosity may also play a role (Pringle et al. 1965; Okada et al. 1982).

The repeated ischemic attacks following vibration exposure produce pathological changes in the artery walls (Ashe et al. 1962). Early cases show medial coat hypertrophy while still retaining the ability to constrict and to open the vessel. Severe cases reveal extensive intima hypertrophy, with near closure of the vessel (and a consequent permanent cyanosis of the digits). The mechanism causing these wall changes is unknown. The increase in bulk of the medial coat seen in early VWF cases is said to be associated with increased sensitivity to cold. Again the mechanism is unknown. Lewis (1949) postulated that the endings of the vasoconstrictor nerves are affected and their sensitivity to cold is accentuated. Marshall et al. (1954) noted that the sensory loss extends more closely to the root of the fingers than does the blanching (see Figure 1-1), again suggesting injured nerves. Magos and Okos (1963) suggested that an overactive biochemical vasoconstrictor mechanism develops within the vessels when they are exposed to vibration, and therefore the hypersensitivity could be due to an accumulation of vasoactive substances such as the prostaglandins and noradrenaline (Azuma and Ohhashi 1982).

To complicate still further what was accepted as a peripheral or segmental phenomenon, some Soviet and Japanese investigators have

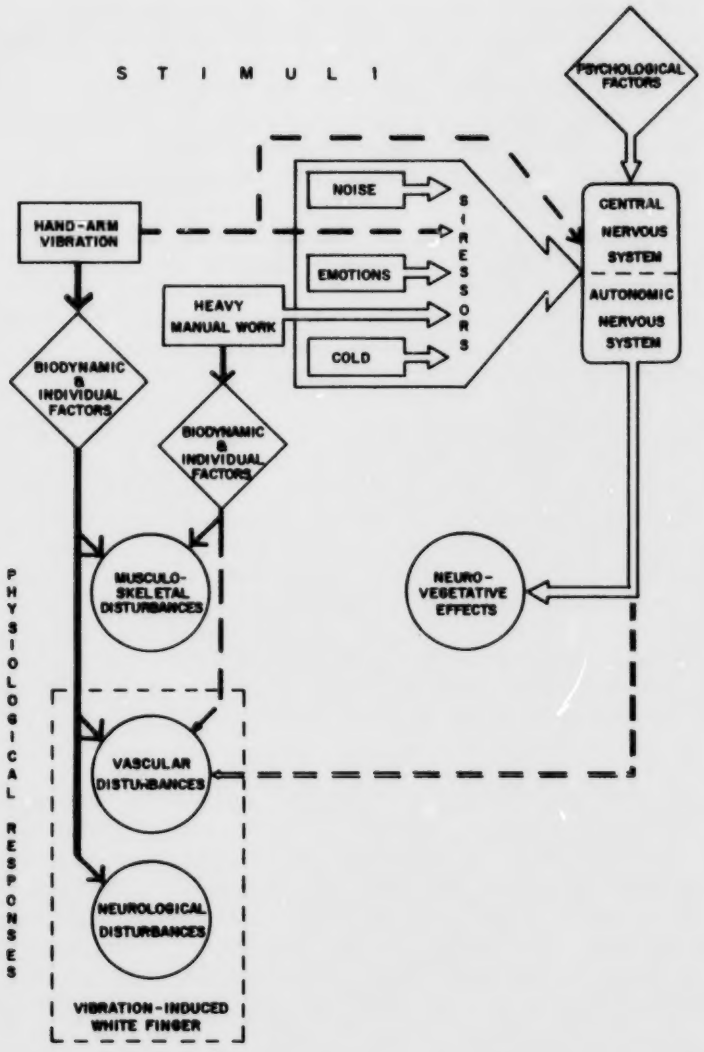
S T I M U L I
PSYCHOLOGICAL FACTORS
NOISE
EMOTIONS
COLD
S T R E S S O R S
HAND-ARM VIBRATION
HEAVY MANUAL WORK
CENTRAL NERVOUS SYSTEM
AUTONOMIC NERVOUS SYSTEM
BIODYNAMIC & INDIVIDUAL FACTORS
BIODYNAMIC & INDIVIDUAL FACTORS
MUSCULO-SKELETAL DISTURBANCES
NEURO-VEGETATIVE EFFECTS
P H Y S I O L O G I C A L R E S P O N S E S
VASCULAR DISTURBANCES
NEUROLOGICAL DISTURBANCES
VIBRATION-INDUCED WHITE FINGER

Figure 1-2. Schematic representation of the various groups of signs and symptoms (circles) and their probable links to the physical and psychological stimuli (rectangles) that occur during hand-arm vibration exposure. Cause-effect relationships are suggested by lines, the more tentative of which are dashed: broad lines - strong links; narrow lines - weak links. Biodynamic, individual and psychological (personality) factors that differ from person to person and so modify the effects of the stimuli are represented by diamonds (the first two are listed in Table 1-3).

suggested that exposure of the hand to vibration affects the entire organism, mediated through the central nervous system. Data have recently been reported showing that operators of certain power tools, principally chain saws, suffer from neurological and psychosomatic symptoms arising from the reflex centers of the brain. These include excessive palmar sweating, vertigo, headache, insomnia, anxiety, irritability, forgetfulness and impotence (Futatsuka et al. 1980).

These neurovegetative effects are symptomatic of a stress syndrome linked to power tool operation, and are probably associated more with the heavy manual work, the intrinsic risk of injury on the job and exposure to noise and extreme temperatures, than with exposure to vibration (Brammer 1983a). The role of these agents, either individually or collectively, in precipitating the vegetative symptoms is at present unclear. Direct transmission of very low frequency vibration from the hand to the head, and hence to the brain, cannot, however, be excluded.

Figure 1-2 attempts to link physiological responses to the physical and psychological stimuli occurring during Hand-Arm vibration exposure. It must be regarded as somewhat speculative in view of our incomplete understanding of the mechanisms involved. In this diagram, strong cause-effect relationships that have already been demonstrated or are believed to exist are shown by broad lines, and weak effects are indicated by narrow lines. Possible relationships are suggested by dashed lines.

1.2 ESTABLISHING SIGNS AND SYMPTOMS CAUSED BY VIBRATION

The signs and symptoms associated with vibration exposure are not unique and need to be distinguished from similar signs and symptoms arising from other causes. Hence, a careful differential diagnosis is required in which Primary Raynaud's Disease is identified by its early onset (60% of persons affected exhibited symptoms by age 30 years), its bilateral, symmetric appearance in response to cold and often to stress, and its familial predisposition. The causes of Secondary Raynaud's Phenomenon must, of course, be excluded.

Secondary Raynaud's Phenomenon is associated with many diseases, including occlusive arterial diseases, neurovascular entrapment syndromes, connective tissue diseases, trauma, and intoxication. A complete list of causes is given in Table 1-1 (Taylor and Pelmear 1975). What these have in common is that their pathophysiological changes all affect blood flow which, when reduced, produces white fingers through changes in pressure gradient, vessel diameter or blood viscosity. Abrupt changes in the vasculature of the fingers may result, however, from injuries (lacerations and fractures) or from freezing (frostbite). In an epidemiological survey of a vibration-exposed population, causes of Secondary Raynaud's Phenomenon

Table 1-1. Causes of Secondary Raynaud's Phenomenon (adapted with permission from Taylor and Pelmear (1975)).

Connective Tissue Disease	Scleroderma Systemic lupus erythematosus Rheumatoid arthritis Dermatomyositis Polyarteritis nodosa Mixed connective-tissue disease
Trauma	1. Direct to Extremities (a) Following injury, fracture or operation (b) Of occupational origin (vibration) (c) Frostbite and immersion syndrome 2. To Proximal Vessels by Compression (a) Thoracic outlet syndrome (cervical rib, scalenus anterior muscle) (b) Costoclavicular and hyperabduction syndromes
Occlusive Vascular Disease	Thromboangiitis obliterans Arteriosclerosis Embolism Thrombosis
Dysglobulinemia	Cold hemagglutination syndrome Cryoglobulinemia Macroglobulinemia
Intoxication	Acro-osteolysis Ergot Nicotine Vinyl chloride
Neurogenic Disease	Poliomyelitis Syringomyelia Hemiplegia

unrelated to vibration exposure may account for a substantial prevalence of the white fingers reported, and so must be identified.

The presence of peripheral nerve degeneration requires a differential diagnosis to include neurological diseases (Juntunen and Haltia 1982). This has proved to be more difficult than for the vascular disturbances, in that changes in the neurological system are not easy to quantify, especially subjective complaints such as tingling, numbness, clumsiness and difficulty controlling fine movements of the fingers. Recently, median nerve compression within the carpal tunnel at the wrist (carpal tunnel syndrome), which results in sensory loss over the median nerve distribution in the fingers (thumb and index, middle and half the ring fingers, on the palmar side), has been recognized as a complication that needs to be excluded.

In the search for degenerative changes in the hand-arm system (blood vessels, nerves, bones, joints, connective tissue) caused by vibration, it has proved difficult in epidemiological studies to differentiate between the effects of vibration and those of heavy manual work - involving constant, repetitive movements of the hands and arms to manipulate the tool or workpiece. Moreover the neurological effects of long-term exposure may be more evident than the circulatory effects, depending on the spectral content of the vibration entering the hands.

1.3 CLASSIFICATION OF SIGNS AND SYMPTOMS BY SEVERITY

The consequences of exposing the hands to vibration are usually related to the frequency of episodic finger blanching, the area affected, and the ease with which the vasospasms are provoked. Outdoor workers exposed to low temperatures are most prone to early morning attacks, especially if they ride bicycles or motocycles to work. When attacks become increasingly frequent, workers report interference with home and leisure activities. These complaints are difficult to quantify but constitute a definite reduction in the "quality of life". When attacks occur year round, persons report that there is interference with the performance of their work, and that their fingers ultimately become stiff and clumsy, which leads to difficulty with fine work and with handling small objects. Some people whose condition becomes this severe find that they are unable to continue working outdoors during cold weather (Laroche 1976). Their decision is probably influenced by the suppression of tactile perception and grip strength that accompanies each exposure, and so occurs daily (Lidström et al. 1982; Pyykkö et al. 1982). These changes, which are in addition to any permanent deterioration in perception threshold, may be sufficient to restrict the ability to hold or control an object, particularly a power tool (e.g. a chain saw) that can cause bodily injury.

Because of the reliance on a person's history of his attacks, it is not surprising that several different schemes for classifying

symptoms and defining the extent of impairment have been developed. Only the two most commonly used classification schemes are considered here.

The Taylor-Pelmear clinical grading of VWF into "Stages" (Table 1-2) has been used extensively in the United Kingdom since 1968, and more recently in the U.S.A., Canada, and elsewhere (Taylor and Pelmear 1975). At Stage 1 (early case) the worker complains of blanching confined to one or more fingertips; there is no interference with work or leisure activities. These early cases usually suffer first from tingling sensations, on and off the job, followed by numbness that may or may not persist after the blanching is noticed. Stage 2 is a transitional phase. At Stage 3 (advanced case) workers have bilateral finger blanching which extends to the base of the fingers, and experience interference with activities at home and at work owing to the frequency and extent of attack. There is an inability to perform fine tasks and there may be paresthesia and disturbance of sleep.

In Japan, the U.S.S.R. and some countries in Eastern Europe, the classification is based on the Soviet work of Andreeva-Galanina and Drogitchina. It consists of "Levels", which again emphasize the person's signs and symptoms (Drogitchina 1971; Matoba et al. 1975). In Level I, Secondary Raynaud's Phenomenon is dormant but there may be numbness and intermittent pain in the fingers and forearm, and light sweating of the palms. In Level II, Secondary Raynaud's Phenomenon occurs occasionally, with increasing numbness, pain, coldness, muscle pain and joint stiffness in the fingers and forearm. A decline in muscle power of the upper arm and gripping force also appears. Dull headaches are often reported, and sweating of the palm increases. In Level III, vasospasms occur more frequently with increased symptoms in the fingers and forearm. There is slight muscle contracture and occasionally ulnar nerve paralysis. Changes in the bones of the elbow joint may be detected and extreme sweating of the palms occurs. Symptoms indicating neurosis, such as anxiety, state of depression and interference with sleep, also appear. Finally, in Level IV, Secondary Raynaud's Phenomenon is very frequent and prominent, and may also appear in the legs. Muscle contracture, peripheral nerve paralysis, and changes in the bones of the elbow joint become apparent. Nervous instability and symptoms indicating neurosis increase further; nausea and dizziness also occasionally appear.

There are clearly substantial differences between these classification schemes and in the emphasis placed by the two schools on the most important components of the HAV Syndrome, the former including only those demonstrably caused by vibration (see Figure 1-2). That operators of vibrating power tools experience the symptoms included in the Soviet classification is not questioned; what is questioned is whether these are associated with tool vibration as opposed to some other facet of the job.

Table 1-2. Taylor-Pelmear classification of vibration-induced white finger by Stages (with permission from Taylor and Pelmear 1975).

Stage	Condition of Digits	Work and Social Interference
0	No blanching of digits	No complaints
0_T	Intermittent tingling	No interference with activities
0_N	Intermittent numbness	No interference with activities
1	Blanching of one or more fingertips with or without tingling and numbness	No interference with activities
2	Blanching of one or more fingers with numbness: usually confined to winter	Slight interference with home and social activities. No interference at work.
3	Extensive blanching: frequent episodes summer as well as winter	Definite interference at work, at home and with social activities: restriction of hobbies.
4	Extensive blanching, most fingers: frequent episodes summer and winter	Occupation changed to avoid further vibration exposure because of severity of signs and symptoms.

Note: Complications are not used in this grading.

1.4 FACTORS INFLUENCING THE SEVERITY OF VIBRATION EXPOSURE

A complete listing of the many factors known or believed to influence the severity of vibration exposure is given in Table 1-3 (Taylor and Pelmear 1975; Färkkilä et al. 1979; ISO 1979; Matsumoto et al. 1979; Griffin 1980; Miyashita et al. 1982). Studies of groups of industrial workers engaged in the same work for many years have shown that the risk of developing the HAV Syndrome increases with the duration of exposure, and with the rate at which vibration enters the hand. The former is determined by the consecutive years of employment involving vibration exposure and the duration of exposure each workday, which are combined by some investigators to form the total operating time (TOT). The latter is determined by the dominant amplitudes and frequencies of the source of vibration, be it a hand-held power tool, a machine or a workpiece (such as a casting being ground), and by the coupling between the source and the hand.

Both source intensity and the source-hand coupling may vary substantially over a period of time, even for the same power tool, or industrial process, and operator. Increases in source vibration usually result from deterioration in the condition of the tool (e.g. from lack of maintenance, excessive wear, and aging), and from a failure to control the efficiency of the work process. Examples of the latter are incorrectly sharpened saw chains and eccentric grinding wheels. A worker can also strongly influence the vibration entering his hands, by how he operates the tool or machine (e.g. speed and throttle controls), by how he holds or supports the tool or workpiece, and by the muscular forces he exerts during the process. Thus, differences in work practices, skill and productivity will lead to variations in the severity of exposure for workers performing the same task with the same tool or machine, by introducing both biodynamic and motivational factors. Biological differences in the susceptibility of humans to vibration also affect the severity of exposure.

A complete specification of exposure would thus require measuring the vibration amplitudes and frequencies entering each hand, and the hand grip forces, in well-defined directions, and perhaps even the surface area and location of flesh in contact with the source, all as a function of time. To monitor daily all these parameters for each worker, including his posture and other factors, is clearly impractical. It is thus necessary to reduce the problem to manageable proportions by identifying those parameters that may be expected to dominate, and hence effectively determine, the severity of vibration exposure. These form the first group listed for each category in Table 1-3.

1.5 PREVENTION AND TREATMENT

That many existing power tools and machines transmit excess vibration to the hands is evidenced by the prevalence of the HAV Syndrome in many occupations (Griffin 1980). The extent to which the

Table 1-3. Factors known or believed to influence the severity of occupational exposure of the hand to vibration (Taylor and Brammer 1982, with permission of John Wiley and Sons).

Physical	Dominant vibration amplitudes entering the hand
	Dominant vibration frequencies entering the hand
	Years of employment involving vibration exposure
	Total duration of exposure each workday
	Temporal pattern of exposure each workday
	Dominant vibration direction relative to the hand
	Non-occupational exposure to vibration
Biodynamic forces)	Hand grip forces (compressive and push or pull
	Surface area, location and mass of parts of the hand in contact with the source of vibration
	Posture (position of the hand and arm relative to the body)
	Other factors influencing the coupling of vibration into the hand (e.g. texture of handle - soft compliant v rigid material)
Individual	Factors influencing source intensity and exposure duration (e.g. state of tool maintenance, operator control of tool or machine work rate, skill and productivity)
	Biological susceptibility to vibration
	Vasoconstrictive agents affecting the peripheral circulation (e.g. smoking, drugs, etc.)
	Predisposing disease or prior injury to the fingers or hands (e.g. trauma, lacerations, etc.)
	Hand size and weight
	Epidemiological factors (e.g. age)

vibration of existing sources may be reduced depends on their principle of operation, and design. Many current designs of power tools would benefit from the addition of vibration-isolation systems to the handles (Miwa 1982), and it seems likely that power tools and machines will in the future be designed to minimize vibration entering the hands (Redwood et al. 1977; Gidlund and Lindqvist 1982).

Until power tools and machines are available that present no risk of developing the HAV Syndrome, preventive measures offer the only means for controlling the potential health hazard, as gloves do little to attenuate vibration at the frequencies of interest (< 500 Hz). The following measures have been suggested by the International Organization for Standardization (ISO 1984):

a) documenting previous vibration exposure;

b) pre-employment screening, to identify those persons with Primary Raynaud's Disease or diseases that may cause Secondary Raynaud's Phenomenon (see Table 1-1) or peripheral neuropathy;

c) an annual medical examination to detect those persons susceptible to the HAV Syndrome;

d) selection of power tools and processes that result in the least severe vibration exposure (see Table 1-3); and

e) training in operating procedures and work practices that minimize the vibration entering the hand. These include:

   i) avoiding continuous exposure by introducing work breaks;

   ii) employing a minimum hand grip consistent with safe operation of the tool or process; and

   iii) wearing appropriate clothing, including gloves to keep warm and reduce the risk of injury.

In addition, Taylor and Brammer (1982) have suggested that it is desirable to remove persons from further vibration exposure at a definite Stage or Level of the HAV Syndrome, preferably Stage 1 or early Stage 2 in the Taylor-Pelmear classification. They also noted that deteriorating cases will require close supervision, in view of the strong epidemiological evidence of a cumulative relationship between some signs and symptoms and the vibration entering the hand.

For persons with the HAV Syndrome, no cure or effective treatment is presently available. Therapy is essentially palliative. Vasodilation of the peripheral vessels by direct action through chemotherapy has been unsuccessful and is dangerous in many cases, owing to undesirable side-effects that affect balance. The failure of drugs

or chemotherapy is due to the absence of a therapeutic agent that acts specifically on the digital arteries. In advanced cases, the sympathetic nerves are either blocked or severed. Vasodilation of the digital vessels following surgery is immediate but, as already noted, the improvement is temporary. Recent reports indicate some success with repeated plasma exchange (Zahavi et al. 1980), though it is difficult to understand the mechanism of this treatment since involvement of plasma fibrinogen, cold hemagglutins or cryoglobulins has not been demonstrated conclusively in VWF. The use of ketanserin has also been reported recently for the treatment of Secondary Raynaud's Phenomenon (Stranden et al. 1982). In addition, some success has been claimed for biofeedback therapy (Sedlacek 1979).

2.0 DOSE-RESPONSE RELATIONSHIPS

Although neurological, vascular and musculo-skeletal disorders have been reported in many occupations in which vibration enters the hands, there have been few attempts to determine dose-response relationships for any symptom attributed to vibration exposure. When completely defined, a dose-response relationship would ideally be applicable to all occupations and workers whose hands are exposed to vibration. It would permit prediction of the onset or progression of one or more components of the Syndrome, and estimation of exposures that could be tolerated during a workday.

It would be unrealistic to suggest that these goals can be completely realized at the present state of knowledge, for several reasons:

1) The various components of the HAV Syndrome may occur independently and progress at different rates (Miyashita et al. 1982; Pyykkö et al. 1982). Several dose-response relationships may therefore be required.

2) It is difficult to establish that some symptoms reported by operators of power tools and industrial processes are caused by vibration as opposed to unrelated disease, heavy manual work or stressors (see Figure 1-2).

3) A successful, objective diagnostic test has not yet been developed for any component of the HAV Syndrome. In consequence, dose-response relationships have to be based on subjective reports of signs and symptoms.

4) There is an inherent limitation in retrospective, cross-sectional epidemiological studies of vibration-exposed populations (which constitute the main source of data), namely that results are influenced by the rates at which persons enter and leave the group.

5) There is a range of individual human responses to vibration (Verrillo 1980; Welch 1980; Nishiyama and Watanabe 1981).

6) Contours of equally hazardous vibrations - that is, combinations of vibration amplitudes and frequencies that present an equal risk of producing one or more components of the Syndrome - are not well-defined.

7) Many physical, biodynamic and individual factors influence the severity of vibration exposure (see Section 1.4).

These considerations have a profound influence on the development of dose-response relationships. Thus, while it will often be possible to establish a typical or "average" response of a population

group to vibration, there will also be a significant variation in response among members of the group. This is illustrated in Figure 2-1 (Brammer 1983a), where the cumulative frequency of a selected symptom is expressed as a function of the duration of group exposure for two exposure rates, one of which (A) is more severe than the other. In this example, the exposure rate is considered to be a single-valued measure of a group's exposure, so that a range of exposure times must be predicted during which the symptom of interest occurs with increasing frequency among group members. Note that the assumption of a single-valued exposure rate is merely a mathematical convenience, which has the effect of transferring all variability in response to the other exposure variable, in this case the exposure duration.

The definition of a typical response of a population group to vibration (e.g. a cumulative frequency of 50% in Figure 2-1) can be attempted only when a large majority of the persons ultimately affected have developed symptoms, perhaps after five years' exposure in case A. In all other cases in Figure 2-1, it is not possible to establish a typical group response without knowledge of the distribution function. Hence, the ability to construct dose-response relationships from population group data will depend not only on the exposure measures selected, but also on the prevalence of the sign or symptom under consideration. This, in turn, is influenced by the rate at which people enter and leave a population group. Control of these epidemiological variables to exclude data from unrepresentative groups inevitably necessitates the imposition of selection rules. If not screened by selection rules, the data from vibration-exposed population groups display considerable scatter (Griffin 1982).

2.1 ONSET OF FINGER BLANCHING

Of the early signs and symptoms of the HAV Syndrome, only the onset of white fingers has been frequently reported in the literature and appears to be recalled with reasonable precision by those affected. The latent interval for blanching of the first fingertip, t_{LIFB}, is thus a physiological response to vibration expressible in terms of duration of exposure. For population groups whose members continue to perform the same work year after year, the probability of group members developing white fingers may be approximated by a normal distribution, when expressed as a function of exposure duration (Brammer 1984). This function is, of course, completely specified by its mean value and standard deviation.

Considerable progress in interrelating different exposure rates, such as are presumed to occur in occupations with different latent intervals, has been made by expressing them solely in terms of a frequency-weighted acceleration component, a_K. The frequency-weighting network employed for this purpose is the reciprocal of the contour for equally hazardous vibrations shown in Figure 2-2 (Brammer 1982a). Its

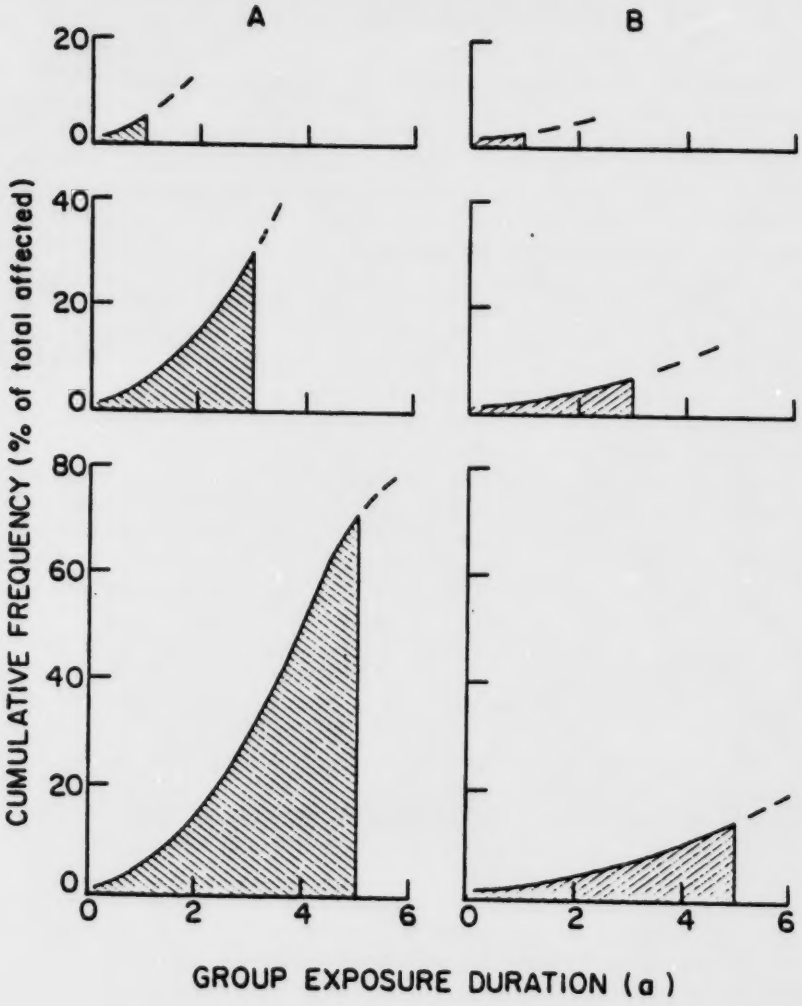

Figure 2-1. Development of a symptom of the Hand-Arm Vibration Syndrome among members of a population group, expressed in terms of the exposure duration of group members. The cumulative frequency within the group is shown after 1, 3 and 5 years for two exposure rates, A and B (Brammer 1983a, with permission of J. Low Freq. Noise Vib.).

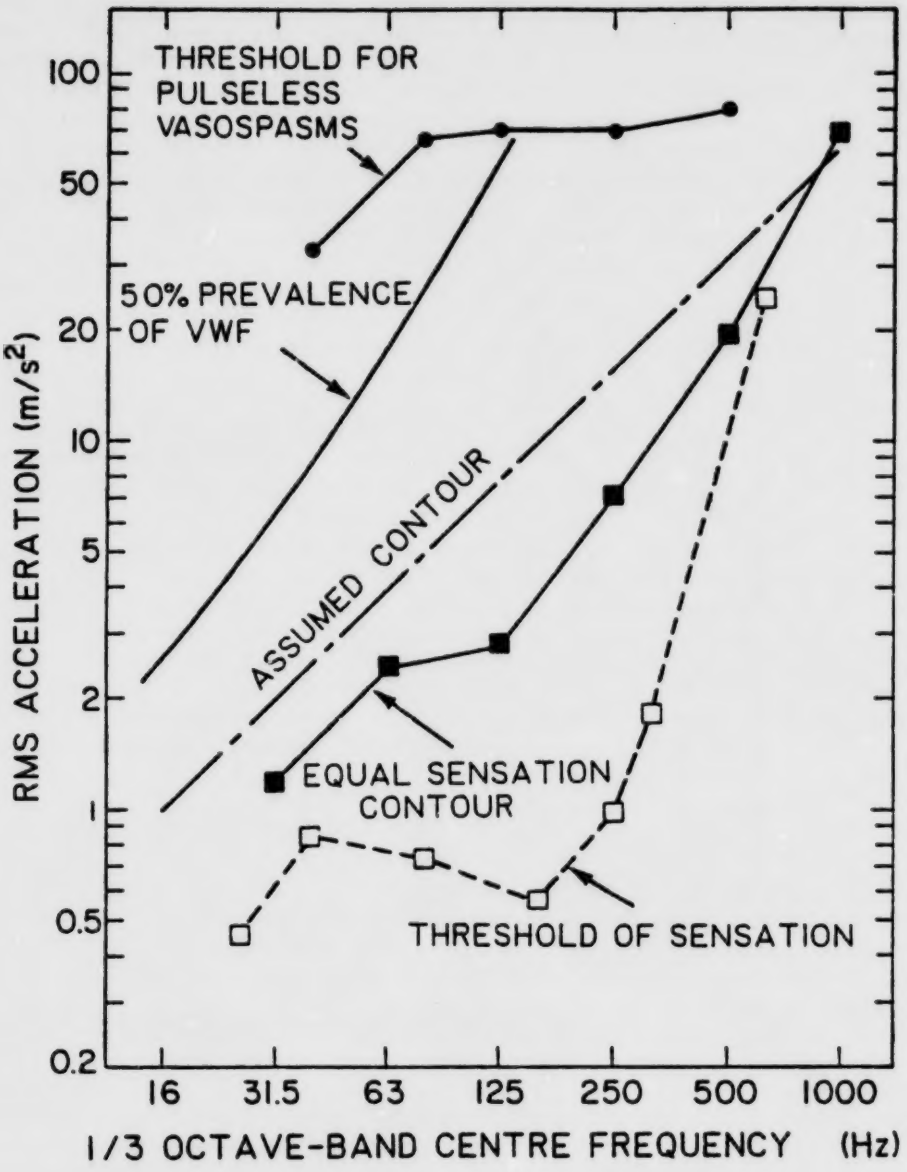

Figure 2-2. Physiological, psychophysical and subjective responses to vibration from which to establish vibration amplitudes at different frequencies that are equally hazardous (Brammer 1982a, with permission of John Wiley and Sons).

shape can be seen to be a compromise between the curves shown, which summarize various physiological, psychophysical and subjective responses to vibration that may reasonably be expected to be associated with the onset of VWF.

The shape of this contour at frequencies below 16 Hz is ill-defined. Measurements of equal tactile sensations at frequencies down to 4 Hz suggest that a contour of equal hazard is better represented by equal accelerations (i.e. a horizontal line in Figure 2-2) than by the equal velocity contour used at higher frequencies (Miwa 1967; Fukuda et al. 1982). The frequency-weighting network derived from this composite contour, shown in Figure 2-3, forms the basis for the determination of a_K from the broad-band acceleration of a vibrating source (ISO 1984). Values of this parameter may be obtained for component vibrations in three orthogonal directions. For these purposes, a system of coordinates centered at the head of, and with its primary (Z) axis along the length of, the third metacarpal has been proposed by the ISO (ISO 1984). In this biodynamic coordinate system, the X axis is normal to the palm so that the Y axis lies in the plane of the hand (see Figure 2-3). A related basicentric coordinate system, more suited to vibration measurements on many tool handles, is also shown in the diagram, in which the origin is located at the hand-source interface and the Y and Z axes are rotated slightly to align the former with the axis of a cylinder gripped between the thumb and the fingers.

The expression of exposure rates in terms of a_K has been attempted only for population groups whose members operate a single type of power tool or are involved in the same industrial process throughout the workday. In these circumstances, an average or typical value of a_K for a population group may be derived from vibration measurements on a subset from the group. Hence, conceptually, all sources of inter-subject variability are incorporated in the distribution function for the latent interval, as in the example contained in Figure 2-1.

The dose-response relationships so obtained are shown in Figure 2-4 (Brammer 1983a). They give the duration of employment prior to the onset of episodes of finger blanching in selected percentiles of a population group exposed to a known, frequency-weighted, root-mean-square (rms), component acceleration (usually the X component of vibration in the coordinate system specified by the ISO). The curves are thus contours of the cumulative frequency of white fingers in a vibration-exposed population, expressed as percentages of the total number of workers ultimately affected. They are based on two empirical equations (Brammer 1982a). The first relates a representative value of a_K measured at a surface in contact with the hand to the mean latent interval for finger blanching in a population group, $\bar{t}_{LIFB}$:

$$\bar{t}_{LIFB} = 78.7/a_K^{1.07} \qquad (1)$$

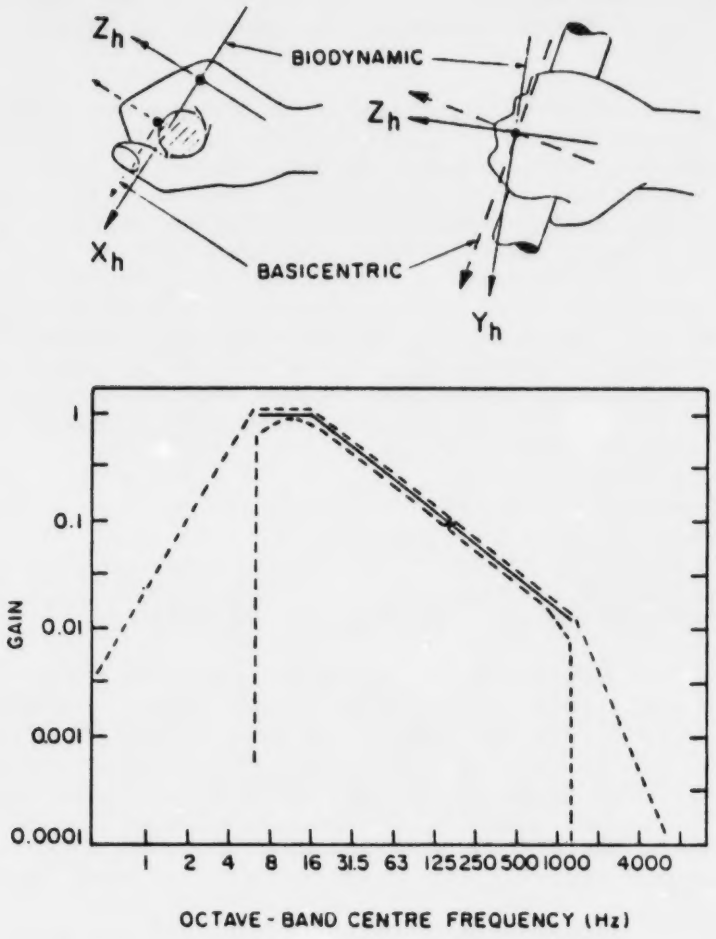

Figure 2-3. (a) Biodynamic and basicentric coordinate systems for the hand, showing directions of the vibration components X_h, Y_h and Z_h.

(b) Gain characteristics of the filter network used to frequency-weight acceleration components (continuous line). The filter tolerances (shown by the dashed lines) and gain outside the frequency range from 5 to 1500 Hz are provisional, and are those contained in ISO (1982).

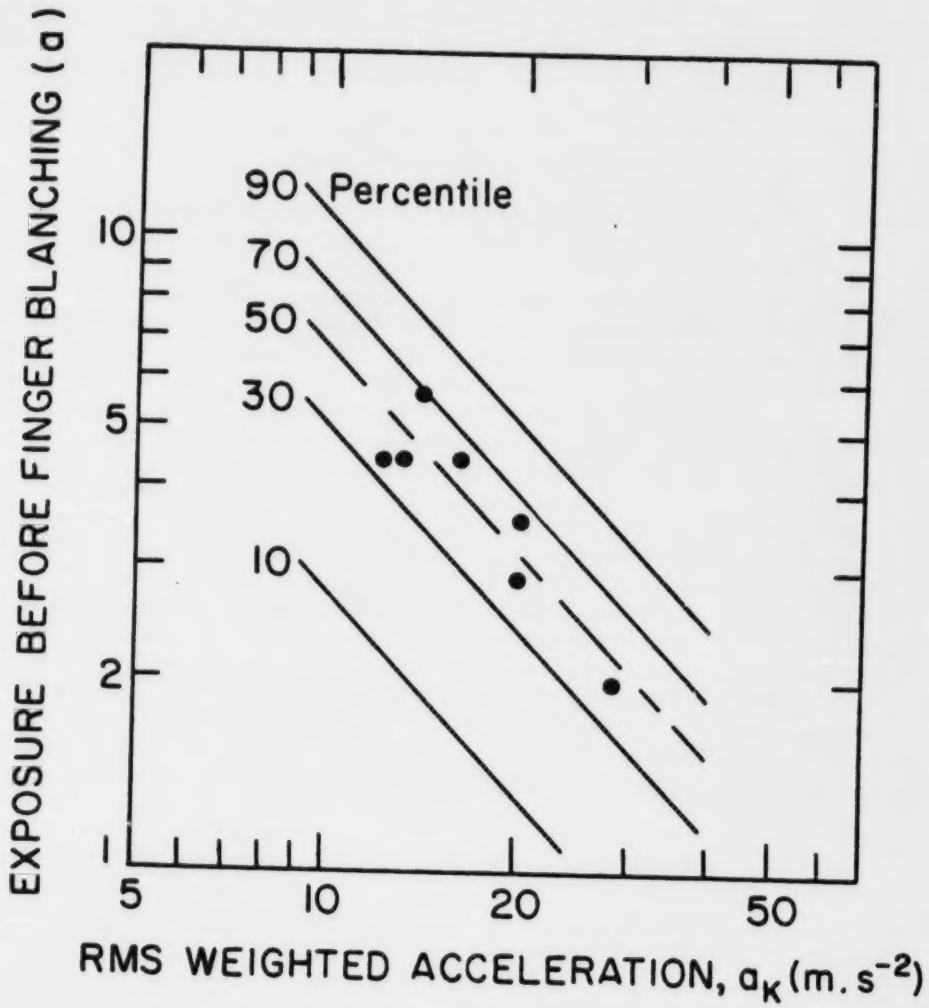

Figure 2-4. Duration of exposure prior to the onset of episodes of finger blanching in members of a population group that is exposed to a known frequency-weighted, rms, component acceleration, expressed as percentages of the total number of persons ultimately affected (Brammer 1983a, with permission of J. Low Freq. Noise Vib.).

The second links the range of exposure times for the onset of episodes of finger blanching in individual members of a population group to the mean latent interval for the group. As the probability of members of a population group developing VWF appears to follow a normal distribution when expressed as a function of exposure duration, this range of exposure times is conveniently expressed by the standard deviation, s, where:

$$s = 0.01 + 0.46\ \bar{t}_{LIFB} \qquad (2)$$

These relationships were derived by applying the selection rules listed in Table 2-1 to every epidemiological study of vibration-exposed persons found in the literature, virtually all of which were cross-sectional and retrospective in nature. These rules attempt to exclude population groups in which members' exposures may not be characteristic of a large population, by imposing a minimum acceptable group size (rule 1). Errors introduced by exposure conditions that result in a low prevalence of VWF within a group (e.g. case B of Figure 2-1) are limited by rules 1 and 2. The exclusion of population groups subject to a large influx and/or efflux of members is not treated explicitly (as no such information is contained in the original studies), but is the reason for rule 3 and for the increase in prevalence with longer latent intervals in rule 2.

Rules 1-3 have been applied to studies in which the average latent interval and its standard deviation were reported for a group of vibration-exposed workers, and rules 1-4 to those containing both the average latent interval and a measure of the tool or process vibration. In the latter case, data from only seven population groups effectively satisfy the selection rules. These are shown in Figure 2-4 by the filled circles, which generate the dashed curve for the 50 percentile.

2.2 DOSE-RESPONSE RELATIONSHIPS FOR OTHER SIGNS AND SYMPTOMS

In the absence of sufficient epidemiological data to independently contruct dose-response relationships for any other sign or symptom of the HAV Syndrome, it is possible to extend the relationships of Section 2.1 to include additional effects of vibration exposure. This may be accomplished, in principle, by linking the rates of progression of other symptoms to the onset of finger blanching, in a population group whose members maintain the same vibration exposure for many years.

Provided appropriate selection rules are devised, it has been suggested that the ratio t_3/t_{LIFB} is independent of the power tool or industrial process, where t_3 is the "average" exposure time reported by persons within the population group in Stage 3 VWF (see Table 1-2). The magnitude of this ratio is estimated to be 3.2 ± 0.2, for a minimum of 15% of a group to reach Stage 3 (Brammer 1982a). The implied dose-response relationship for at least this segment of a population group is

Table 2-1. Rules for selecting epidemiological data (Brammer 1983a, with permission of J. Low Freq. Noise Vib.).

For each population group:

1. The group must consist of at least 30 persons whose full-time occupation involves operation of a particular type of vibrating power tool or industrial process throughout the workday, at least 20 of whom must experience episodes of finger blanching.

2. The minimum prevalence of finger blanching within the group must be 50% if the latent interval is less than six years, and 75% if the latent interval is greater than six years.

3. On average, the duration of vibration exposure for group members must exceed the latent interval reported by those affected.

4. A recognized experimental technique must be used to measure the vibration entering the hands of group members (see, for example, ISO (1979)).

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hence parallel to that for the onset of finger blanching but displaced in time by a factor of 3.2, as indicated in Figure 2-5 (Brammer 1983a).

The establishment of further ratios independent of the tool or process vibration for other symptoms of the HAV Syndrome would appear desirable, but no such analysis has been attempted. However, a recent survey involving large populations of shipyard and foundry workers has included, for the first time, careful estimates of the latent intervals for tingling, numbness and blanching (Behrens et al. 1982). These data suggest that the ratio of the median latency for numbness to that for finger blanching, t_{LIN}/t_{LIFB}, may be independent of the exposure rate. The magnitude of this ratio for the two populations is close to 0.6, though it must be emphasized that both used the same types of pneumatic chipping and grinding tools (the symptoms, however, developed at rates that differed by a factor of almost 10). This possible dose-response relationship is included in Figure 2-5, although it must be considered extremely tentative.

2.3 LIMITATIONS AND ACCURACY

Perhaps the most limiting feature of the dose-response relationships is the small number of studies used in the derivation of the crucial relationship between the frequency-weighted, rms, acceleration component and the average latent interval for blanching of the first white fingertip (the dashed line in Figure 2-4). Of thirteen published epidemiological studies containing vibration measurements considered in the analysis, approximately one-half do not clearly fulfill one or more selection rules. Fortunately, data from several common occupations in which vibration is transmitted to the hands do satisfy the requirements. These include operation of chain saws (3 studies), rock drills (2 studies), hand-held grinders (1 study), and pedestal grinding machines (1 study). In each of these, the nature of the work was such that vibration entered the hand discontinuously throughout the workday. In other respects, however, the work environments were very different, involving both indoor and outdoor operations, and the use of rotary tools powered by electric motors or internal-combustion engines, of percussive pneumatic tools, and of machines in which the workpiece was hand-held.

The range of exposure parameters used in the derivation of the relationship between t_{LIFB} and a_K is restricted to values of the former from 2 to 5.7 years, and of the latter from 12 to 28 $m.s^{-2}$. One perhaps unexpected reason for the exclusion of studies with shorter latent intervals and greater accelerations is concern with the accuracy of vibration measurements, particularly those involving percussive pneumatic tools (Taylor and Brammer 1982). In contrast, the main reason for the rejection of studies with long latent intervals is the prevalence requirement contained in rule 2. As formulated, this rule

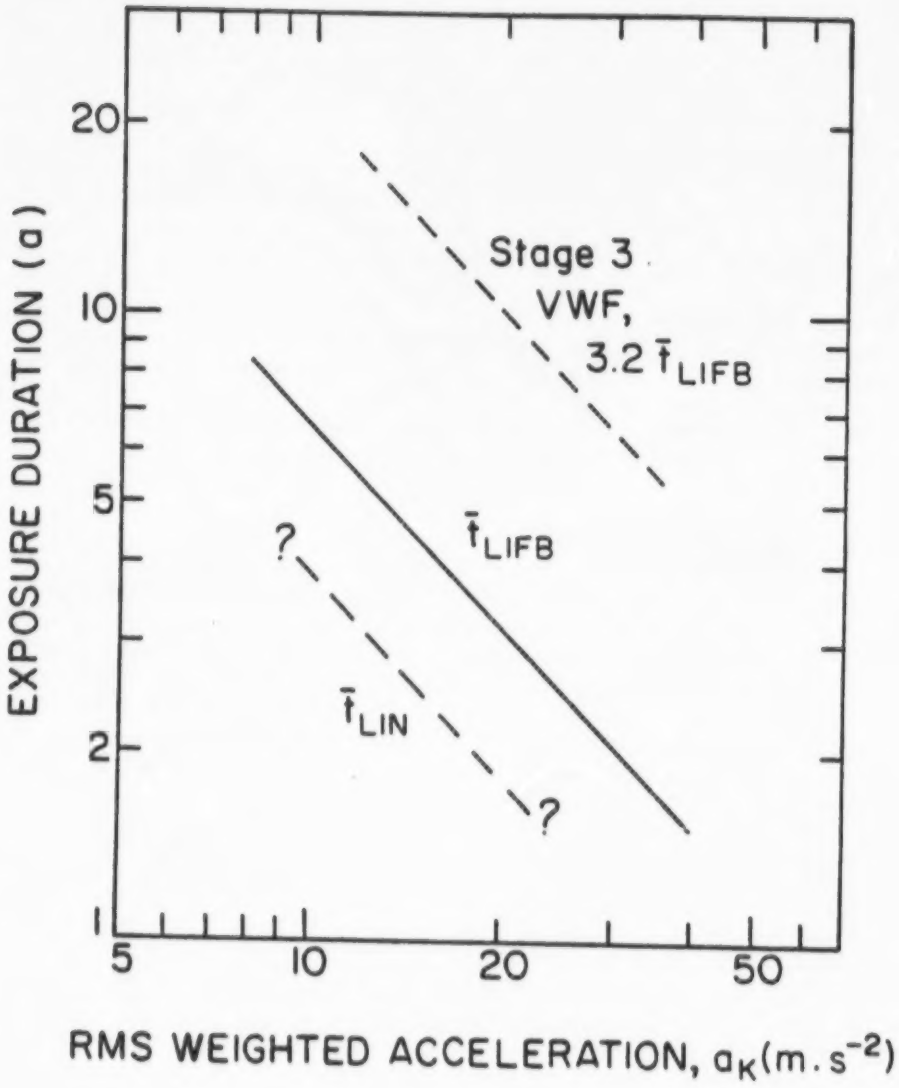

Figure 2-5. Application of dose-response relationships for the onset of finger blanching to other symptoms of the Hand-Arm Vibration Syndrome. The average latent interval for finger blanching serves as the basis for a probable dose-response relationship for Stage 3 VWF, and a possible relationship for the latency of finger numbness, t_{LIN} (Brammer 1983a, with permission of J. Low Freq. Noise Vib.).

cannot differentiate population groups with a low prevalence of white fingers, resulting from exposure to low-level vibration, from those with abnormally low prevalence caused by the withdrawal of group members suffering from the HAV Syndrome.

For these reasons, and because of some remaining uncertainty in the contour of equally hazardous vibrations, particularly at low frequencies, it is difficult to estimate directly the accuracy of the dose-response relationships. At first sight, the spread of the data used in the derivation of Eq. 1 (see the filled circles in Figure 2-4) is such that considerable variation in its gradient would appear possible, as well as an alternative functional form. Both of these potential sources of error are amplified by extrapolating the dose-response relationships beyond the range of values for which data are available. Their accuracy may hence be inferred by comparing, for example, independent methods for estimating the vibration threshold (that is, the value of a_K below which symptoms of the HAV Syndrome do not occur even after prolonged, near-daily exposure). This subject is treated in Section III, where it is found (see Table 3-2) that the dose-response relationships in Figure 2-4 are unlikely to be significantly in error.

Even though the data base is limited and the accuracy of the dose-response relationships is difficult to estimate, there is no reason for not applying such relationships provisionally to other groups of workers similarly exposed, i.e. to persons who work full-time at operating one type of vibrating power tool or who are involved in the same industrial process throughout the workday. It should be noted that the relationships cannot be expected to apply to population groups in which a rapid change in membership occurs.

3.0 TOLERABLE EXPOSURE TO VIBRATION THROUGHOUT THE WORKDAY

In this Section, a tolerable exposure to vibration is defined for persons whose hands are exposed throughout each workday. This exposure will be considered to be the threshold for the onset of symptoms which, in turn, can be derived from epidemiological studies of workers whose full-time occupations involve habitual operation of a vibratory power tool or machine. A quantitative estimate of the threshold can be obtained from two types of epidemiological data:

a) prospective studies of selected cohorts of workers; and

b) cross-sectional, retrospective studies of population groups (of workers) who continue to perform essentially the same task with nominally identical tools or machines.

In either case, the development of the initial disturbances must have been linked in some way to a quantitative measure of the vibration exposure.

Only one prospective study satisfies this requirement, and the results of individual retrospective studies are inconsistent unless subjected to some selection process, such as that described in Section II. There have been, however, three independent attempts to express the data from retrospective studies in a form from which a vibration threshold could be derived. The four methods are discussed separately in the following subsections.

3.1 EXTRAPOLATION OF DOSE-RESPONSE RELATIONSHIPS

The concept of a vibration threshold implies avoiding the onset of the HAV Syndrome during a working lifetime, it being understood that the effects of vibration exposure are cumulative. In terms of the dose-response relationships, this is equivalent to predicting the frequency-weighted, rms, component acceleration corresponding to a latent interval in excess of, say, 25 years. However, the relationships derived by Brammer (1982a) are based on epidemiological studies in which the mean latent interval ranged from 2 to 5.7 years (Eq. 1) and from 1.6 to 21.5 years (Eq. 2). Extrapolation of the former to latent intervals of the order of 25 years requires confidence in the accuracy and functional form of the equation.

The derivation of functional relationships between exposure of the hands to vibration and the development of white fingers was dependent on the application of the rules in Table 2-1, which were designed to ensure that the data selected are representative of the effects of vibration on man. Thus, the requirement that the prevalence of white fingers in a population group be 75%, while appropriate for

the establishment of meaningful dose-response relationships from cross-sectional epidemiological data, needs to be relaxed to examine the consequences of long-term exposure to low-level vibration. This single change to the selection rules permits data from population groups in which the onset of disorders commenced only after many years of exposure to be included in the analysis, provided the tool or machine vibration is known. The initial low prevalence of VWF in a population group exposed to vibration is evident in Figure 3-1, where cumulative reports of the latent interval for finger blanching (the closed squares) are shown as a function of the duration of exposure (Brammer 1982b).

If it is further assumed that with prolonged exposure to vibration of sufficient intensity, the prevalence of VWF in a cohort of workers ultimately reaches 100%[a], then it is possible to predict the "average" latent interval reported by a cohort with a low prevalence of white fingers (Brammer 1982b). In this way, epidemiological data from population groups with long latent intervals and low prevalences of symptoms may be compared with the extrapolated dose-response relationships.

Unfortunately, there are no cohort data that satisfy the relaxed selection rules with which the extrapolated dose-response relationships may be compared. In these circumstances, there is little alternative but to consider epidemiological data from cross-sectional studies, even though persons entering and those leaving a population group during the course of exposure may significantly influence the prevalence of disorders observed. Consequently, agreement between the values reported in and predicted for cross-sectional studies can provide some confidence in the extrapolated dose-response relationships; however, disagreement between them suggests only that either a significant change in group membership occurred during the exposure, or that the extrapolation is in error, or both.

An example of the calculation of prevalence for a cross-sectional study that satisfies the selection rules (Table 2-1), and so is believed to be representative of the development of VWF, is shown in Figure 3-1. The continuous curve shows the prevalence of white fingers as a function of exposure time predicted from the component acceleration measured on the tool handles. The latent intervals reported by group members (the closed squares) and the mean value derived from these data (the triangle within a circle) can be seen to be in reasonable agreement with the predictions.

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[a] Prevalences of VWF in excess of 95% have been reported in cross-sectional, retrospective studies. See, for example, Taylor and Pelmear (1975).

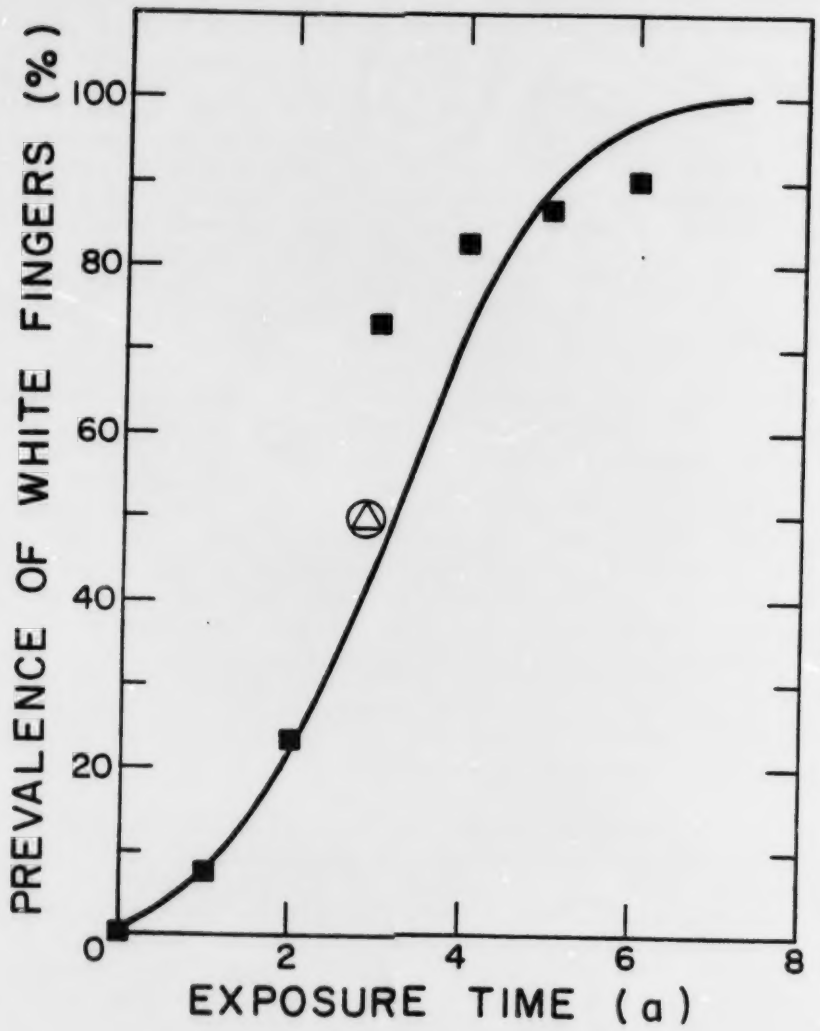

Figure 3-1. Cumulative reports of the latent interval for finger blanching in a population group expressed as a function of exposure duration (closed squares). The mean latent interval for the group is shown by the triangle within a circle. The onset of finger blanching predicted from the tool vibration is shown by the continuous line (Brammer 1982b, with permission of John Wiley and Sons).

There is only one cross-sectional study rejected by the selection rules, solely because of the low prevalence of white fingers, that does contain information on the onset of disorders in a population group with a long latent interval. A comparison between the calculated and reported latent intervals for this population group is shown in Figure 3-2 (Brammer 1982b). It is evident that the value predicted (shown by the dashed line) is in good agreement with the low prevalence epidemiological data (the open circle). To obtain this prediction, the relationship between t_{LIFB} and a_K had to be extended to a component acceleration of 3 $m.s^{-2}$, and to a mean latent interval in excess of 24 years. Extrapolation of the dose-response relationships to latent intervals of this magnitude and to population segments other than 50%, without revision of their functional form, thus appears justified on the basis of the available epidemiological data.

The duration of exposure prior to the onset of episodes of finger blanching in selected percentiles of a cohort may thus be calculated with some confidence from the tool, machine or workpiece vibration. Results are given in Table 3-1 for frequency-weighted, rms, component accelerations from 1 to 25 $m.s^{-2}$, and for population percentiles from 10 to 50% (Brammer 1982b). Because the extreme percentiles of a distribution are most sensitive to the exact shape of the distribution curve, no attempt has been made to estimate latent intervals for percentiles less than 10%. Predictions for persons with an average response to vibration, corresponding to the 50 percentile, and for the 10% of persons within a cohort most susceptible to vibration are shown in Figure 3-3. The values in Table 3-1 and Figure 3-3 are identical to those adopted by the ISO for the new Draft International Standard on Hand-Arm Vibration (ISO 1984).

It is evident from these results that at small values of the component acceleration, small changes in a_K correspond to large changes in exposure time prior to the onset of finger blanching, for all population percentiles. Hence, there is little need to specify the duration of a working lifetime with great precision. Reference to Table 3-1 and Figure 3-3 therefore suggests that the vibration threshold lies in the range $1 < a_K < 2.9$ $m.s^{-2}$. The upper extreme of this range corresponds to the component acceleration predicted to delay the appearance of white fingers, on average, for 25 years. The lower extreme corresponds to the component acceleration predicted to delay the appearance of white fingers for over 30 years in the 10% of the population most susceptible to VWF.

3.2 PREDICTIONS FROM COMPARISONS OF DATA FROM CROSS-SECTIONAL, RETROSPECTIVE, OCCUPATIONAL SURVEYS

3.2.1 MIURA AND CO-WORKERS' EPIDEMIOLOGICAL STUDIES AND VIBRATION MEASUREMENTS

An extensive comparative survey of the onset of the HAV Syndrome in working populations has been conducted in Japan (Miura et

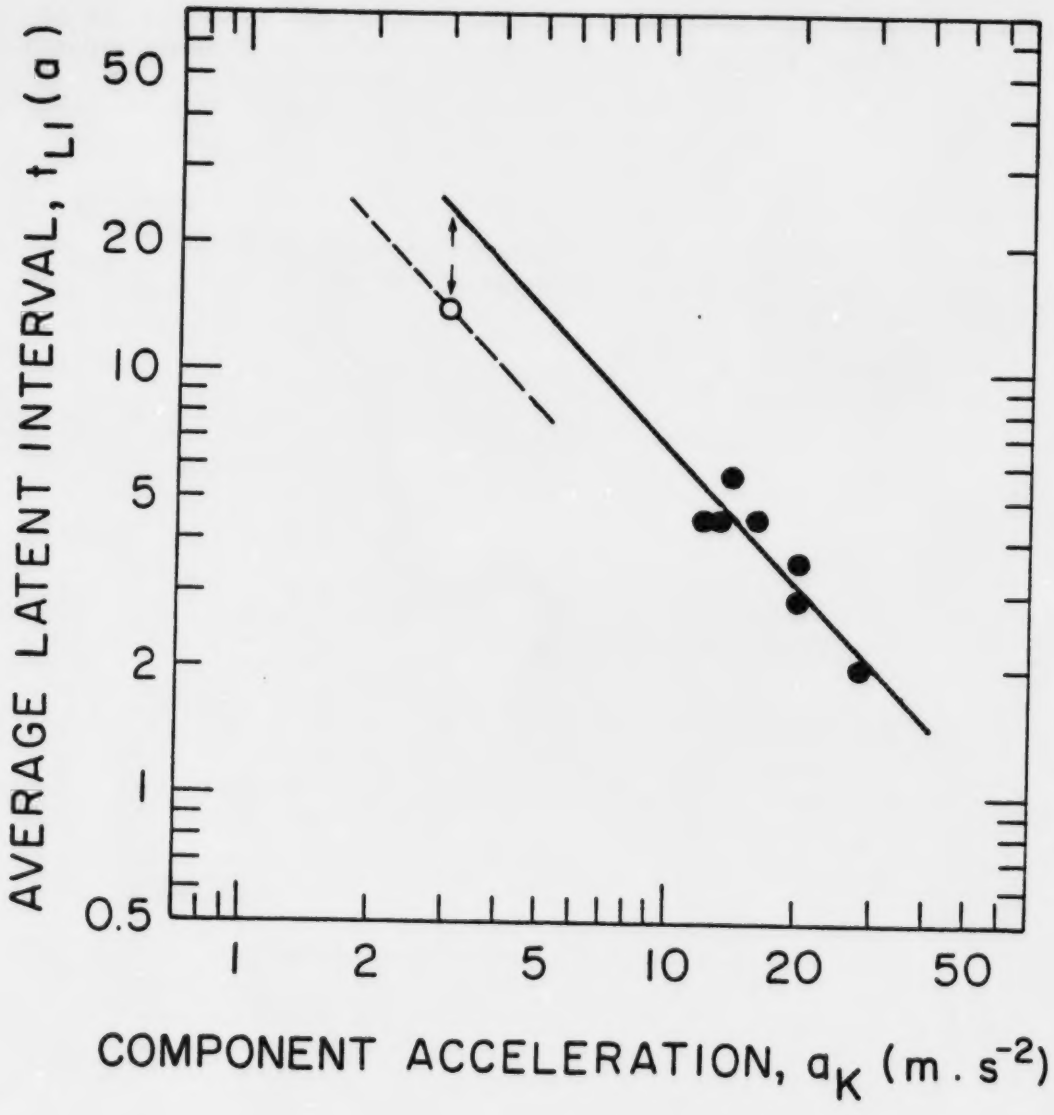

Figure 3-2. Extrapolation of the dose-response relationships (to the extent shown by the small arrows) to predict the median latent interval for a population group with a prevalence of 37% (dashed line) compared with data from a group with this prevalence operating hand grinders (open circle). The exposure conditions observed were: a_K = 3 m.s^{-2}; "average" t_{LIFB} = 13.7 a; and prevalence of white fingers = 37%. The data shown as filled circles were used in the derivation of Eq. 1 (continuous line) (Brammer 1982b, with permission of John Wiley and Sons).

Table 3-1. Predicted duration of exposure prior to the first episode of finger blanching for selected percentiles of a cohort exposed to a given frequency-weighted, rms, component acceleration throughout the workday (Brammer 1982b, with permission of John Wiley and Sons).

Frequency-Weighted, rms Component Acceleration	Exposure Duration[a] (a) Population Percentile				
a_K ($m.s^{-2}$)	10	20	30	40	50
25	-	-	-	2.2	2.5
20	-	2	2.4	2.8	3.2
15	-	2.7	3.3	3.8	4.3
12	2.3	3.4	4.2	4.9	5.5
10	2.7	4.1	5.1	5.9	6.7
8	3.5	5.2	6.5	7.5	8.5
6	4.7	7.1	8.8	10	12
5	5.8	8.6	11	12	14
4	7.3	11	14	16	18
3	10	15	18	21	24
2	15	23	28	33	-
1	32	-	-	-	-

[a] Durations of less than 2 a or in excess of 35 a are shown by -.

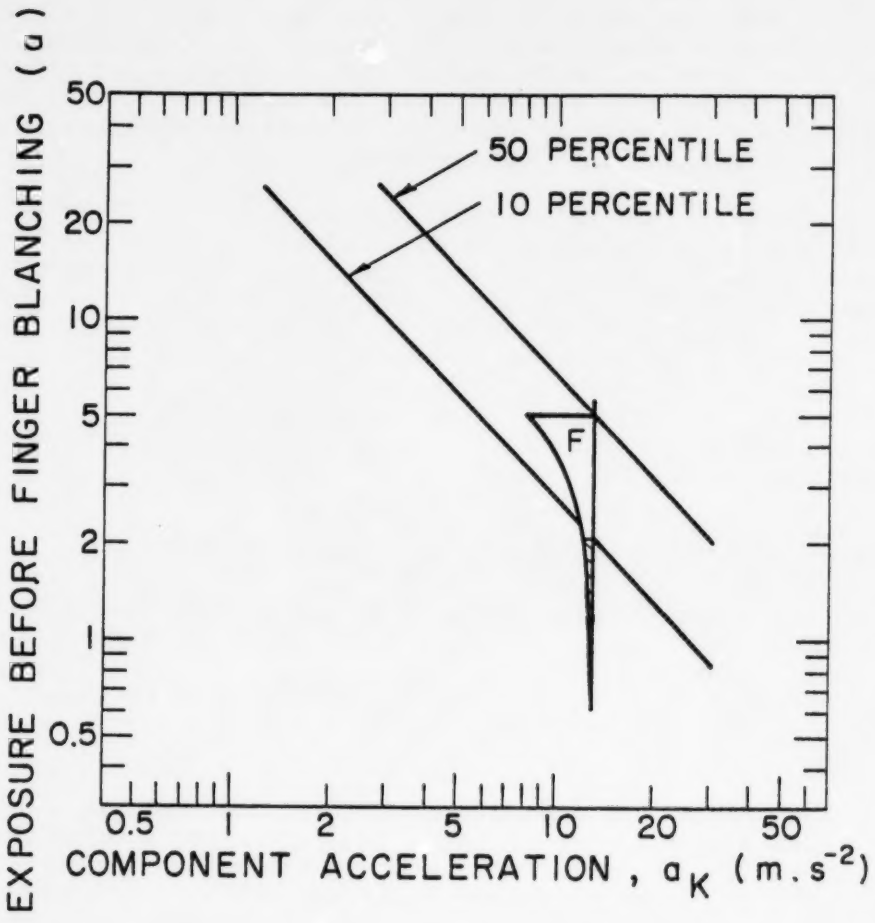

Figure 3-3. Predicted duration of exposure prior to the first episode of finger blanching for selected percentiles of a cohort exposed to a given frequency-weighted, rms, component acceleration, a_K, throughout the workday. The cumulative distribution function (F) is also sketched (adapted from Brammer 1982b, with permission of John Wiley and Sons).

al. 1950). The prevalence of signs and of symptoms reported by workers from a range of occupations was first obtained by a cross-sectional, retrospective study. The epidemiological data were then compared with measurements of the dominant vibration frequency and the corresponding displacement of each source of vibration entering the hands. The results are summarized in Figure 3-4, where the sources have been separated into three groups: piston-operated pneumatic tools (closed circles), portable rotary tools (open circles), and fixed rotary machines, where the operator holds the workpiece (triangles). Some impression of the range of power tools, machines and occupations studied may be derived from the figure caption.

Based on these data and a knowledge of the disorders associated with prolonged operation of each tool or machine, it is possible to deduce a contour linking vibration amplitudes and frequencies at which the same prevalence of symptoms is expected to occur. According to Miura et al. (1950), the line in Figure 3-4 corresponds to the vibration threshold below which no workers complained of "numbness, paleness or chill of the fingers". This contour is equivalent to values of the frequency-weighted, rms, component acceleration in the range $1 < a_K < 2.1$ m.s^{-2}, depending on the frequency.

3.2.2 GRIFFIN'S ANALYSIS OF THE LITERATURE

A comprehensive review of epidemiological studies in which the prevalence and latency of the earliest signs or symptoms of the HAV Syndrome (usually tingling or numbness) and the source vibration were determined, has been undertaken recently by Griffin (1982). Several trends in these measures were found by comparing the results in a number of ways.

Figure 3-5 shows prevalence data from cross-sectional studies in which the frequency-weighted, rms, component acceleration can be derived at a surface in contact with the hand. It is evident that there is a trend towards increasing prevalence of tingling or numbness with increasing vibration entering the hand, though there is a broad spread in the data. Griffin (1982), however, found no published reports of symptoms from exposures in which the frequency-weighted component acceleration was less than 1 m.s^{-2}. This value may thus be presumed to represent an estimate of the vibration threshold for the onset of any sign or symptom of the HAV Syndrome.

3.3 PREDICTION FROM PROSPECTIVE STUDIES

There has been only one prospective study of cohorts of workers in which both the development of vibration-induced disorders and the vibration exposure have been repeatedly evaluated (Taylor et al.

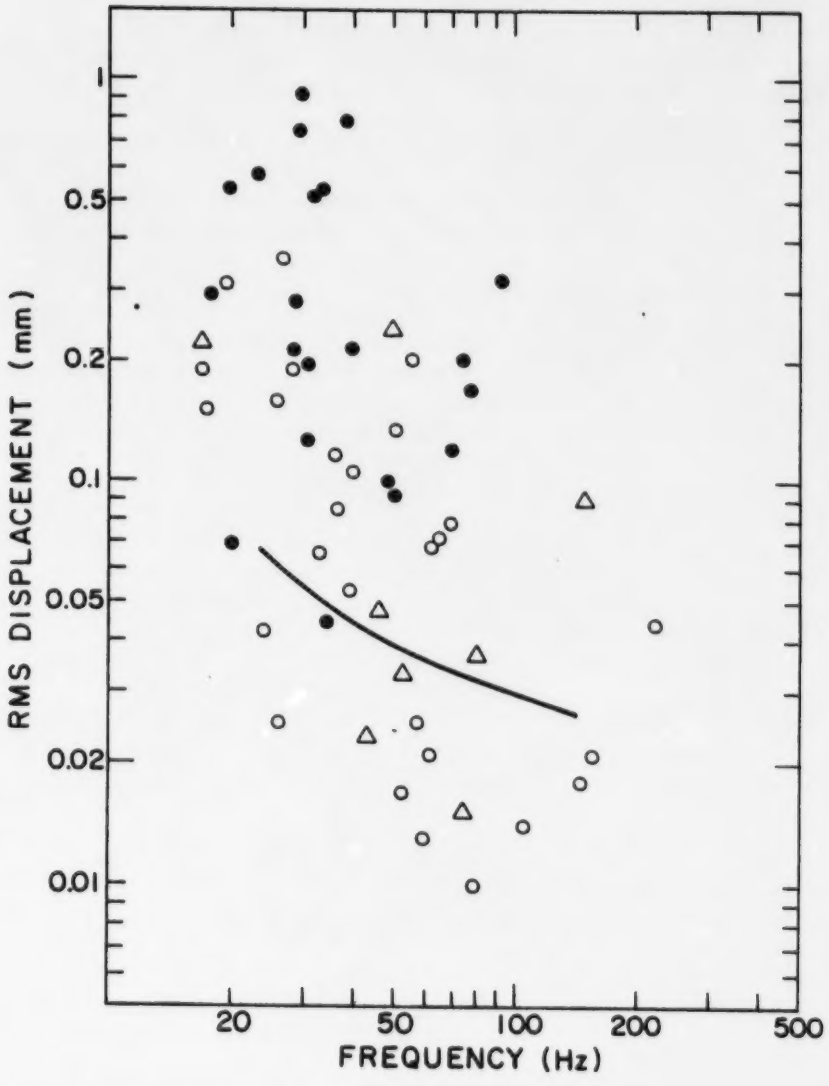

Figure 3-4. Maximum, narrow-band, rms displacements (mm) of a range of hand-held power tools and machines, expressed as a function of their fundamental vibration frequency. Data shown by closed circles are for rock drills, air hammers, rivetting hammers, chipping hammers, a concrete breaker and a sand rammer; data shown by open circles are for hand grinders, swing grinders, hand sanders, hand drills, a chain saw and an impact wrench; data shown by triangles are for stand-mounted metal polishers and grinders (Brammer 1982b, with permission of John Wiley and Sons).

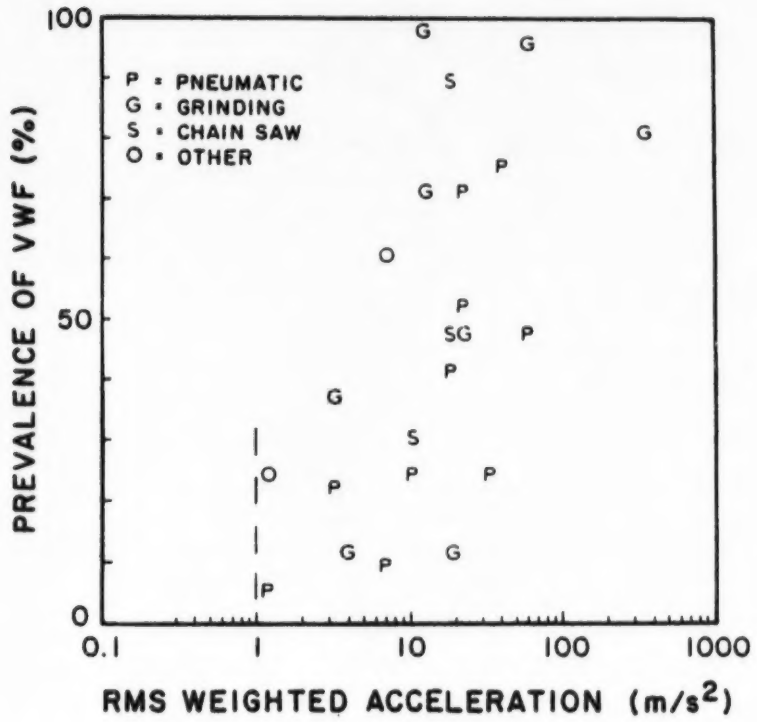

Figure 3-5. Relationship between the prevalence of VWF and the frequency-weighted, rms, component acceleration of the power tool, or workpiece, used by 23 population groups. Source categories: P - pneumatic tools; G - grinding; S - chain saw; and O - other (adapted from Griffin 1982, with permission of John Wiley and Sons).

1977). In this annual survey of a group of forest workers, the prevalence and severity of vascular signs and neurological symptoms were determined in 46 sawyers, each of whom operated the same model chain saw. The vibration of the saw model used each year was also measured. The results are shown in Figure 3-6 for Stage 0, Stage 3 and Stages 1+2+3 VWF, in the Taylor-Pelmear classification (Table 1-2). The frequency-weighted, rms, component acceleration of the saws is shown in the lower part of the diagram.

It is evident from Figure 3-6 that a significant reduction in vibration occurred after approximately seven years' exposure, coincident with the introduction of saws with vibration-isolated handles. Reference to the upper part of the diagram reveals that the reduction in vibration was followed by a gradual decline in the overall prevalence of VWF (Stages 1+2+3), and a marked decline in the prevalence of Stage 3. It can thus be deduced that the vibration threshold for VWF must be below a_K = 20 $m.s^{-2}$, though whether it lies above or below the frequency-weighted component acceleration of the saws with reduced vibration (a_K ~ 3-5 $m.s^{-2}$) cannot be established from these data. However, a more recent survey by Taylor and co-workers of a second cohort from this population, whose members have operated saws only with vibration-isolated handles, has identified some cases of VWF (Riddle and Taylor 1982). Hence it appears that the vibration threshold must lie below a frequency-weighted component acceleration of ~4.7 $m.s^{-2}$ (the average component acceleration of the saws with vibration-isolation).

3.4 VIBRATION THRESHOLD

Four methods have been described for establishing a threshold for the onset of the HAV Syndrome in persons whose full-time employment involves the operation of a power tool, machine or industrial process in which vibration is transmitted to the hands. The predictions are summarized in Table 3-2 (Brammer 1983b). Although all the methods have limitations, each provides an important contribution to the specification of a vibration threshold.

The dose-response relationships provide the only functional expressions linking vibration exposure to the development of VWF. From these the frequency-weighted, rms, component acceleration necessary to delay sufficiently the onset of finger blanching can be calculated for any percentile of a cohort of workers performing the same task. To obtain these results, the dose-response relationships must be extrapolated to long latent intervals and low prevalences of symptoms. Also, the relationship between the appearance of the first white fingertip and other early symptoms of the HAV Syndrome cannot be specified precisely at the present time.

The results of the survey in Japan by Miura et al. (1950) are not entirely comparable with those of other methods, because the

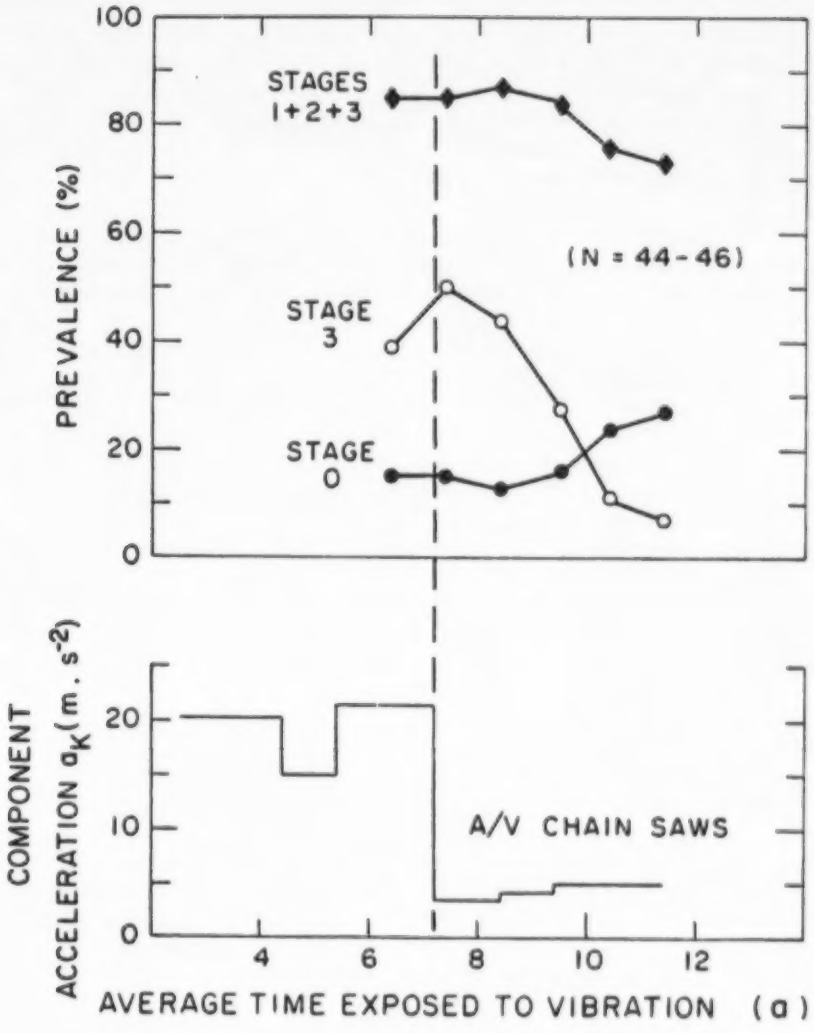

Figure 3-6. Prevalence of selected VWF Stages in a prospective study of a cohort of chain saw operators (upper diagram), in which the frequency-weighted, rms, component acceleration entering the hands decreased significantly with the introduction of saws with vibration-isolated handles (lower diagram) (Brammer 1982b, with permission of John Wiley and Sons).

Table 3-2. Vibration threshold for the Hand-Arm Vibration Syndrome derived by four methods (expressed as a frequency-weighted, rms, component acceleration in $m.s^{-2}$) (Brammer 1983b).

Onset of tingling or numbness		Onset of White Fingers	
Miura and Co-workers[α]	Griffin	Extrapolated Dose-response relationships[β]	Taylor and Co-workers
1 - 2.1	1	1 - 2.9	< 4.7

[α] Value depends on the dominant vibration frequency.

[β] Onset of episodes of finger blanching delayed for the duration of a working lifetime.

threshold values correspond only to the contribution to the frequency-weighted component acceleration at the dominant vibration frequency. The inclusion of contributions from the source vibration at other frequencies could increase these values, perhaps by as much as 50%. Also, it would not have been possible to obtain information pertaining to the completion of a working lifetime from active workers, and so the vibration measured could well permit the onset of disorders within this period. In addition, cross-sectional studies tend to underestimate the prevalence of disorders, owing to the tendency for those suffering severely from VWF to withdraw from vibration exposure (i.e. to change employment). A correction for these two underestimates of the potential hazard of vibration exposure would lead to a reduction of the vibration threshold given in Column 1 of Table 3-2. In the absence of further information on the magnitude of these three (opposing) systematic errors, no adjustment to the accelerations in Column 1 is considered appropriate. Nevertheless, despite uncertainty concerning the precise value of the vibration threshold obtained by this method, it alone can provide a confirmed lower boundary for the onset of vibration- induced disorders, by including data from population groups n o t suffering from any sign or symptom of the HAV Syndrome.

Griffin's (1982) analysis is similarly open to the criticism of all comparisons of data from cross-sectional studies: namely that the reported prevalence of VWF is affected by uncontrolled changes in membership of each population group and by differences between group exposure durations. However, it avoids a major limitation of the comparative survey by Miura et al. (1950), by including only studies in which the vibration measurements could be expressed in terms of a frequency-weighted, rms, component acceleration. The agreement between the results obtained by the two methods (see columns 1 and 2 of Table 3-2) is therefore encouraging. By including data from studies in many countries by different research workers, Griffin's (1982) analysis further avoids several potential criticisms of Miura's data (Miura et al. 1950): specifically, the results are peculiar to epidemiological factors such as ethnic group, working conditions in Japan, or to the experimental procedures employed.

The prospective study by Taylor et al. (1977), in contrast, contains information on the progression of disorders in a controlled population exposed to a known source of vibration. As such, it provides the only estimate of the vibration threshold that explicitly avoids errors arising from the efflux and influx of group members during the course of exposure. Although the population is completely defined and the vibration at the hand is measured repeatedly throughout the exposure, the prospective study can confirm only the progression or appearance of symptoms resulting from this stimulus. Hence, a vibration threshold cannot be specified precisely, though the more recent data indicate that it must lie below a frequency-weighted, rms, component acceleration of 4.7 $m.s^{-2}$ (Riddle and Taylor 1982).

When considered together, the four methods provide complementary evidence for the magnitude of the vibration threshold. Thus, the possibility that the extrapolated dose-response relationships are significantly in error is to a large extent eliminated by their prediction of a threshold range similar to that deduced from the two comparisons of data from cross-sectional surveys. The possibility that these three methods are systematically in error by the same amount is limited, for the upper boundary of the threshold, by the results of the prospective study (and for the lower boundary by the comparative survey data from 15 occupations, shown in Figure 3-4, in which no symptoms were observed). Furthermore, the vibration threshold for the onset of the neurological symptoms (columns 1 and 2) is, on average, somewhat less than that for the onset of vascular signs (columns 3 and 4), a result consistent with the possible dose-response relationship for t_{LIN} in Figure 2-5.

It thus appears that the vibration threshold for the HAV Syndrome lies in the range $1 \leq a_K \leq 2.7$ m.s^{-2}, where the upper extreme has been defined by the arithmetic mean of the upper boundaries of the results in Table 3-2. As both the dose-response relationships predict, and the low-prevalence data shown in Figures 3-2 and 3-5 confirm, long-term exposure to a frequency-weighted component acceleration of 3 m.s^{-2} will lead to a substantial prevalence of VWF. A conservative estimate for the upper boundary of the vibration threshold, consistent with all the epidemiological data, would therefore be somewhat less than this value.

3.5 TOLERABLE EXPOSURES

From the preceding discussion, exposure to a frequency-weighted, rms, component acceleration of 1-2 m.s^{-2}, or less, would appear to be necessary to prevent the onset of disorders in persons whose full-time employment involves an operation whereby vibration enters the hands throughout the workday. More precise specification of a tolerable exposure from the results of Section III is probably not justified, owing to the potential for error in each method. Even so, the maximum rms value of a_K tolerated by the hand before symptoms occur can be defined with sufficient precision to serve as a goal for the design of new, and improved, power tools and machines. It should be noted that the vibration of many power tools and industrial processes currently exceeds these values (Miwa and Yonekawa 1974; Hempstock and O'Connor 1975; Brammer 1978).

In addition to information concerning the onset of disorders, the specification of a vibration limit for the purposes of regulating occupational exposure to vibration involves socioeconomic and other

considerations beyond the scope of this monograph[α]. Vibration limits based solely on the expected adverse health effects have been developed, however, by a committee of the International Organization for Standardization (ISO). The limits were apparently derived from subjective assessments of "unpleasant" vibrations, equal sensation contours, and the transmission of vibration into the hand-arm system (Griffin 1980). The two most recent proposals containing limits applicable to daily exposures from four to eight hours are listed in Table 3-3 (ISO 1979; 1980). The presumed ameliorative effect of exposure interruptions is included in the first Draft International Standard, ISO/DIS 5349 (1979), through relaxation of the limit with increased duration of the vibration-free time period per hour, T. In this proposal, the maximum relaxation of the vibration limit for intermittent exposure in which the total, cumulative, daily exposure remains between four and eight hours is a factor of four. In contrast, no adjustment for interruptions appears in the most recent ISO (1980) draft to contain a vibration limit[β], which instead proposes for the limit a frequency-weighted, rms, component acceleration in the range $2 < a_K < 4$ m.s^{-2}.

It is evident that only the lower extremes of the limits contained in Table 3-3 are compatible with a tolerable exposure specified from epidemiological studies (in which vibration entered the hands discontinuously throughout the workday). From the discussion of Section 3.4, there is considerable evidence that habitual exposure to a frequency-weighted component acceleration of 3 m.s^{-2} or more will lead to the onset of vibration-induced disorders during the course of a working lifetime.

[α] This subject has recently been examined by the American Conference of Governmental Industrial Hygienists and a Provisional Threshold Limit Value (TLV) is to be published in 1984 (ACGIH 1984).

[β] As a matter of policy, the ISO Committee no longer attempts to specify limits for vibration exposure, but rather to define dose-response relationships. An annex to the second Draft International Standard for Hand-Arm Vibration Exposure ISO (1984) contains the dose-response relationships for the onset of finger blanching given in Section 3-1.

Table 3-3. Limits for four-to-eight hour daily exposure to vibration specified in recent ISO proposals (expressed as a frequency-weighted, rms, component acceleration in $m.s^{-2}$).

T^{α} ($min.h^{-1}$)	ISO/DIS 5349, 1979 (ISO 1979)	ISO/TC 108/SC 4 Draft 1980 (ISO 1980)
$0 < T < 20$	1.4	2-4
$20 < T < 30$	2.8	2-4
$30 < T < 40$	4.2	2-4
> 40	5.6	2-4

[α] T is the recurrent time interval without vibration exposure.

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